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THREE DIMENSIONAL STRUCTURES OF SOLAR ACTIVE REGIONS

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ABSTRACT

Three-dimensional structure of an active region is determined from observations with the Very Large Array (VLA) at 2, 6, and 20 cm. This region exhibits a single magnetic loop of length $\sim 10^{10}$ cm. The 2 cm radiation is mostly thermal bremsstrahlung and originates from the footpoints of the loop. The 6 and 20 cm radiation is dominated by low-harmonic gyroresonance radiation and originates from the upper portion of the legs or the top of the loop. The loop broadens toward the apex. The top of the loop is not found to be the hottest point, but two temperature maxima on either side of the loop apex are observed, which is consistent with the model proposed for long loops. From 2 and 6 cm observations it can be concluded that the electron density and temperature cannot be uniform in a plane perpendicular to the axis of the loop; the density should decrease away from the axis of the loop.

INTRODUCTION

The three dimensional structure of magnetic fields above active regions in the low corona and chromosphere-corona transition zone can be determined from multiwavelength radio observations. Radio methods of measuring magnetic fields in active regions are based upon the measurement of total intensity (I) and circular polarization (V) and the use of precise knowledge of the generating mechanisms of radio emission in active regions. The circular polarization in the gyroresonance absorption process which is relevant for sunspot associated sources is due to the fact that for typical conditions in the corona, the extraordinary mode becomes optically thick at the levels where $f = 3\ f_H$ or $2\ f_H$ (f_H = gyrofrequency), whereas the ordinary mode becomes optically thick at the level $f = 2\ f_H$ which is located at a lower level in the sun's atmosphere; the circular polarization in the extraordinary mode then results as a consequence of the temperature structure above active regions. In the free-free process, the circular polarization results from the fact that in the presence of a magnetic field the absorption coefficient in the extraordinary mode is higher than that in the ordinary mode; consequently, the $\tau = 1$ level in the e-mode occurs higher in the solar atmosphere than in the o-mode. Both these processes have been used to estimate magnetic field strengths at centimeter and millimeter wavelengths (Alissandrakis et al. 1980; Kundu et al. 1977; Kundu and McCullough, 1972). The circular polarization maps can be used as chromospheric and coronal magnetograms provided there is no radio wave propagation effect, which can be verified from the correspondence of the radio polarities with those of the photospheric magnetic field.

Aside from the magnetic field structure, the knowledge of the structure of an active region as a function of height is important. This is especially so when the active region appears in the form of a loop as is often the case at centimeter wavelengths. Three dimensional active region studies have been reported by Shevgaonkar and Kundu (1984) from multifrequency observations using the VLA. They studied a region that exhibited a single loop without any other interacting loop nearby.

OBSERVATIONS

Figure 1 shows the total intensity (I) and circular polarization (V) maps at 2, 6 and 20 cm wavelengths. The 2 cm radiation ($\sim$ 80% polarized; $T_b \sim 1.5 \times 10^5$ K) comes from two isolated spots which are co-spatial with two strong magnetic regions with opposite polarities, the sense of polarization being of the same sign as the magnetic fields on the magnetogram. Thus, the 2 cm radiation appears to originate from the foot points of a magnetic loop. The 6 cm total intensity map again shows two regions ($T_b \sim 4.5 \times 10^6$ K; $p \sim$ 10-15%), approximately at the same positions as the 2 cm regions, but larger in size. The larger size of the two regions at 6 cm compared to that at 2 cm, indicates that, if the active region emission originates in a loop, the loop must be diverging towards its apex. The existence of two isolated regions at 6 cm, with $T_b \sim 4.5 \times 10^6$K indicate that the two legs of the loop have not started closing, and that the 6 cm radiation originates from the upper part of the legs of the loop. At 20 cm, the two regions are almost merged into each other but still keep their identity as two regions. The centers of these two merging regions are again co-spatial with the 6 cm peaks within the errors of measurement. The size of the two 20 cm regions is larger than that at 6 cm, but the peak T_b has decreased to $\sim 2.5 \times 10^6$K and p is $\sim$ 20%.

The maps at different wavelengths obviously give sectional views of a magnetic loop at different heights. The magnetic field diverges along the loop in the upward direction. The loop seems to start closing at a height of $\sim 50 \times 10^3$ kms, where the 20 cm radiation originates. The 2 cm polarization data indicate that the extraordinary mode is optically thick in the transition zone, with $T_e \sim 1.5 \times 10^5$K, and the ordinary mode becomes optically thick at a lower level (i.e. for a lower harmonic), with $T_e \lesssim 10^5$K or it is optically thin. Shevgaonkar and Kundu concluded that the 2 cm radiation is dominated by thermal bremsstrahlung and originates from a layer where $N_e \sim 10^{10}$ cm^{-3} and B $\sim$ 2000 G. The T_b at 6 cm is $\sim 4.5 \times 10^6$K and polarization is $\sim$ 15%. Since polarization is low, the gyroresonace radiation has to be optically thick for both modes. Taking $\alpha \approx 45^0$, $L_B = 10^9$ cm, $N_e = 4 \times 10^9$ cm^{-3}, the highest harmonic for which both modes are optically thick is 3, resulting in B $\sim$ 600 G at a height of $\sim 10^4$ kms. Assuming that the same magnetic field diverges with height, the conservation of the magnetic flux requires that if B is $\sim$ 600 G and 2000 G respectively at 6 and 2 cm, the ratio of the source sizes at 6 cm and 2 cm should be $\sim$ 3.5, in contrast to the observed ratio of $\sim$ 24. This difficulty was overcome by asssuming that in the outer rim of the magnetic pole, the 2 cm T_b is $<$ 10% of its peak value, which requires the optical depth to be $\lesssim$ 0.1. Shevgaonkar and Kundu showed that the observations could be explained if N_e decreases by a factor of 3 from the core to the outer rim and B decreases towards the edge of the loop by a factor of 1.76 if T is taken constant or even more slowly if a cool core model is assumed, consistent with the combined high resolution microwave and soft x-ray observations of Strong et al (1984). If the magnetic field remains constant over the outer rim, the conservation of flux gives magnetic pole size $\sim$ 2.5 times that of the 2 cm region, the same as the pole size in the magnetogram.

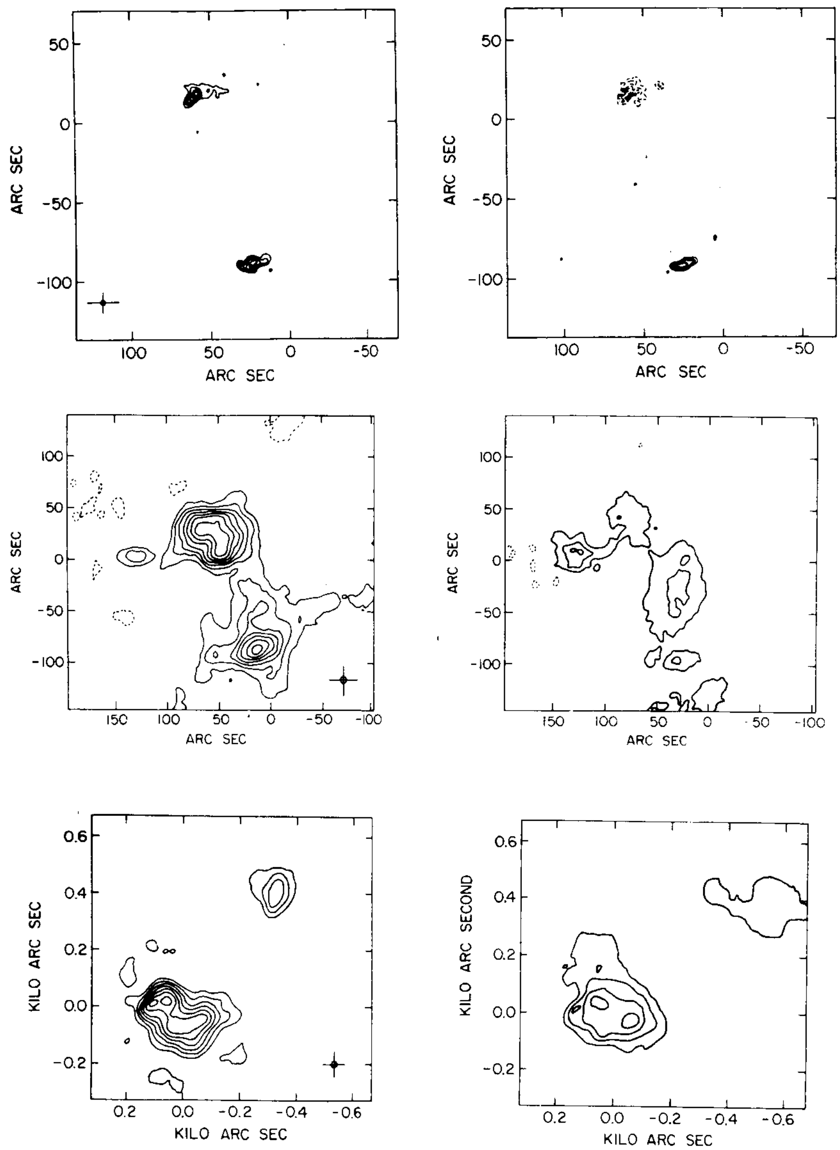

Fig. 1. Total intensity (left) and circular polarization (right) maps of an active region at 2 cm (top), 6 cm (middle) and 20 cm (bottom), made with the VLA with resolution of 2", 5" and 20" arc respectively. At 2, 6 and 20 cm, peak $T_B = 1.5 \times 10^5$ K, 4.6×10^6 K and 2.3×10^6 K respectively; the corresponding contour intervals are 2.9×10^4 K, 5.9×10^5 K and 3.1×10^5 K. For V-maps, the contour intervals are 1.9×10^4 K, 2.2×10^5 K and 1×10^5 K respectively.

At 20 cm, the radiation ($T_b \sim 2.5 \times 10^6$ K, $p \sim 20\%$) originates from the upper portion of the legs of the loop. According to the loop model with uniform energy deposition function along the loop (Rosner et al. 1978), the loop apex should be hottest and so T_B at 20 cm level must be at least 5×10^6K, the same as the 6 cm T_B. But since the observed T_B is $\sim 2.5 \times 10^6$K, the radiation must be optically thin with $\tau \sim 0.7$ to satisfy Rosner et al's model. For a source of dimension 5 x 10^9 cm, N_e required to make $\tau \sim 0.7$ due to thermal bremsstrahlung should be $\sim 4 \times 10^9$ cm^{-3}, or an emission measure of $\sim 10^{29}$ cm^{-5}. This emission measure is higher by about one order of magnitude than that computed by Lang, Willson and Gaizauskas (1983) from VLA observations and by Vaiana and Rosner (1978) from X-ray observations. From magnetic flux conservation, the source size at 20 cm compared to that at 6 cm gives a magnetic field of ~ 150 G at 20 cm level, which is sufficient to generate the 3rd or 4th harmonic gyroresonance emission at 20 cm. Thus, the 20 cm radiation must be due to gyroresonance absorption. For s=3, $\tau_{res} \sim 10^3$ for both modes. By reducing N_e, it does not seem that the radiation can be made optically thin for s=3. Thus, T_e must be 2.5 x 10^6K. For $N_e \sim 10^9$ cm^{-3} or an emission measure of $\sim 10^{28}$ cm^{-5} the region is optically thin due to thermal bremsstrahlung for $T_e \sim 2 \times 10^6 - 5 \times 10^6$ K, which can not explain the observed high T_b of $\sim 2.5 \times 10^6$ K. Lang, Willson and Gaizauskas (1983) concluded from their VLA observations that the 20 cm radiation ($T_b \sim 0.5 \times 10^6$ K) was optically thin bremssstrahlung, with $T_e \sim 2 \times 10^6$ K. However, to get $T_b \sim 2.5 \times 10^6$ K as observed by us, gyroresonance mechanism has to be invoked. Thus, the higher layer from which the 20 cm radiation originates is cooler than the lower layer from which the 6 cm radiation originates. This result does not support Rosner et al's model of uniform energy deposition along the loop, which gives maximum temperature at the apex of the loop. On the other hand, our observations provide evidence for Vesecky et al's (1979) model, according to which the temperature maximum need not necessarily occur at the apex of the loop but there could be two maxima, one on either side of it and a minimum at the apex of the loop.

CONCLUDING REMARKS

We have determined the three-dimensional structure of an active region from observations made with the Very Large Array (VLA) at 2, 6, and 20 cm. The region concerned is a single magnetic loop of length $\sim 10^{10}$ cm. The 2 cm radiation is found to be mostly thermal bremsstrahlung, originating from the footpoints of the loop. The 6 and 20 cm radiation is dominated by low-harmonic gyroresonance radiation, originating from the upper portion of the legs or the top of the loop. The loop broadens toward the apex. The top of the loop is not found to be the hottest point, but two temperature maxima on either side of the loop apex are observed, which is consistent with the model proposed for long loops. From 2 and 6 cm observations we conclude that the electron density and temperature cannot be uniform in a plane perpendicular to the axis of the loop; the density should decrease away from the axis of the loop.

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